FLUIDIC THRUST VECTORING NOZZLES

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SUMMARY

There is a great deal of interest in India in the fluidic thrust vectoring of fixed geometry, exhaust nozzles of low-observable super-maneuverable, unmanned combat air-vehicles (UCAVs) . This paper gives an overview of the recent work carried out at the Propulsion Division, CSIR-National Aerospace Laboratories on Fluidic Thrust Vectoring.

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Presentation at the Workshop on "Thrust Vectoring Nozzles of Aero-Engine", GATET, DRDO held at the Aeronautical Society of India, 29th March 2014.

INTRODUCTION

Currently, high-performance, highly maneuverable combat aircraft employ mechanical thrust vectoring nozzles (Fig. 1). Although these nozzles are very effective, they have many disadvantages like weight, complexity, sluggishness and the crucial high IR signature (Fig.2). Hence, there have been serious efforts to develop light weight, fixed-geometry, nozzles which use fluidic thrust vectoring for unmanned, stealth combat air vehicles. Fig 2 summarizes the advantages and disadvantages of mechanical and fluidic thrust vectoring systems. It is imperative that whichever thrust vectoring system is used, on deployment, the distortion of engine turbomachinery should be negligible. This requirement indicates the necessity of providing an upstream insulating choked plane to prevent any subsonic disturbances caused by the vectoring from propagating upstream to affect the smooth working of the aero-gas turbine.

Fig. 3 shows the different methods of fluidic thrust vectoring used, depending on the Mach number of the nozzle exhaust. Figs 4a - 4c and Table 1 give details of these systems. The fluidic thrust vectoring systems that are based on " virtual nozzle internal aerodynamic surface shaping" and which have been studied at NAL are shown in Fig. 5. In mechanical systems, the nozzle internal passage shapes are modified by mechanical means to allow for throttling and vectoring. The question then arises whether an equivalent internal shaping could be achieved aerodynamically by careful injection of compressor bleed air circumferentially and axially along the nozzle internal passage. It is needless to say that the allowable bleed air pressure will have to be restricted to below that of the high pressure compressor delivery pressure. However, bleeding of compressor air results in a severe penalty in loss in the engine performance. Hence, an alternative could be to have a dedicated APU which could supply the necessary bleed air, leaving the main engine air flow unaffected.

Detailed studies on the aerodynamic blockage of transverse jet arrays were carried out to determine the jet interaction characteristics and also its equivalence to mechanical blockage. The significant parameters which affect the jet interaction and hence the aerodynamic blockage were the ratio of jet injection pressure to duct air pressure, duct Mach number, the injector port diameter and the injector array configuration. This knowledge of the equivalent aerodynamic blockage of a transverse air jet array allowed designs of the position, sizing and configuring of the jet array to create an equivalent nozzle virtual internal surface shaping to allow throttling and vectoring (Figs. 6 -9)

This knowledge of transverse jet interaction was initially applied to the concept of nozzle throat skewing (Fig 10). In this method, air was injected both at the throat as well as at a carefully selected position in the divergent section of a convergent-divergent nozzle to create a skewed sonic plane which allowed subsonic turning of the exhaust flow. This method leads to far lower total pressure losses than shock vector control which results supersonic turning of the exhaust jet with its consequential shock losses. Figs. 11-15 give details of the NAL experimental set-up and typical experimental results. This concept has been shown, elsewhere, to be valid even for multi-axis thrust vectoring (Fig 16).

Unmanned combat air vehicles (UCAVs) employ dry aeroengines which have only convergent nozzles that are choked. In the absence of a divergent section of the nozzle, the nozzle throat skewing method cannot be employed. Hence, a novel concept of employing virtual aerodynamic internal surface shaping with separation control was evolved by NASA (Fig 17). This 2D technique, which is also known as the dual-throat nozzle (DTN) has two throats separated by a trough containing separated regions when there is no vectoring. To vector, air is injected at or near one vertex of the first throat. The main engine flow is deflected as shown in Fig 17, to achieve the required vectoring. Figs. 18-22 show the salient features of the developmental work carried out at NAL. The second throat will necessarily have to be larger than the first throat to allow for the increased air flow due to the bleed flow as well as for the loss in total pressure to ensure that the controlling throat shall always be the first throat to insulate the main engine working during the vectoring process. This method, however, has the critical disadvantage in that the height of the nozzle is limited. To overcome this disadvantage, NAL has evolved a variant by introducing an immersed strut within the nozzle passage between the throats. The air flow is effectively divided into two passages. This method is particularly effective when the nozzle is elliptically shaped and not the usual 2 D rectangular. Bleed air is fed transversely from the nozzle roof and the immersed strut upper surface to effectively but partially block the upper air passage. The engine flow is then diverted more to the lower passage and due to the internal shaping of the nozzle floor effective modulated upward vectoring takes place. The procedure is reversed for downward vectoring. (Figs.23-28). The immersed strut could also be configured for multi-axis vectoring. The shape of nozzle roof, floor, immersed strut as well as the air injector port array configuration and the ratio of the injection pressure to the duct air pressure are critical parameters for the success of the method.

CONCLUDING REMARKS

The Propulsion Division, NAL has built-up a comprehensive, experimentally validated, design data base for the Fluidic Thrust Vectoring of sonic and supersonic aero-engine exhausts, using the concepts of shock vector control and virtual aerodynamic internal surface shaping ((nozzle throat skewing and separation control (dual throat and its variant with an immersed strut))

ACKNOWLEDGEMENTS

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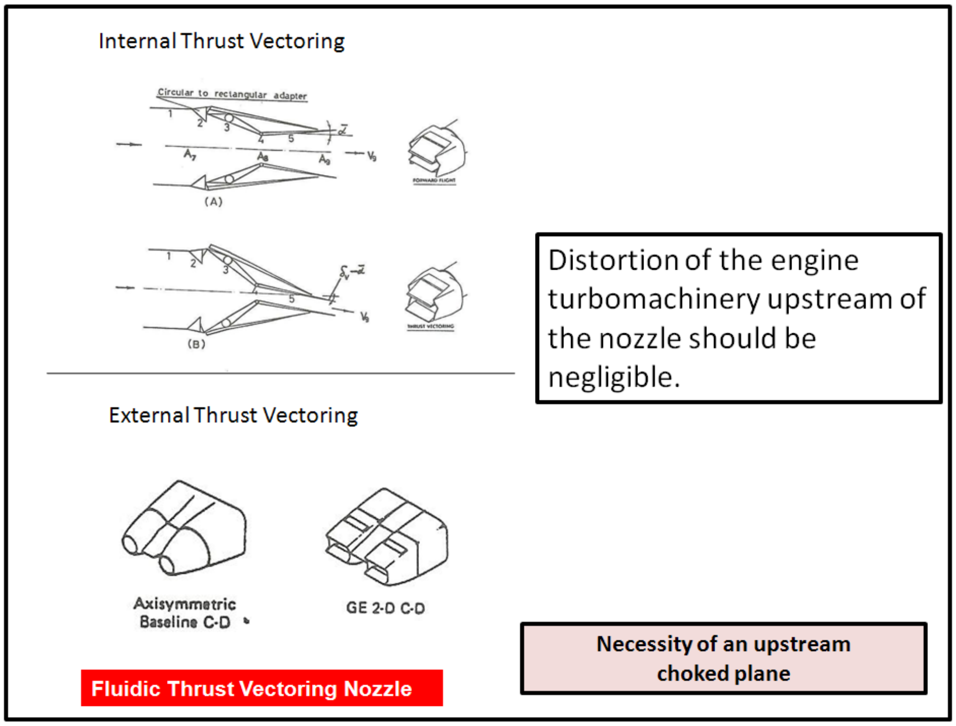


Fig. 1 (Ref. Vectored propulsion Supermaneuverability & Robot Aircraft, Recent Advances in Military Aviation, Benjamin gal-Or, Springer Verlag, N.Y., Heidelberg, 1990)

Disadvantages of mechanical thrust vectoring

- **Heavy and complex**
- **Difficult to integrate**
- **Expensive to maintain**
- **Aerodynamically inefficient**
- **Prone for detection because of high IR signature**

There is a technical need for the ability to control and vector the engine exhaust jet with a constraint that the nozzle be mechanically simple and have as much fixed structure as possible.

Advantages of fluidic thrust vectoring

- **Simple in construction and has no moving parts**
- **Easy to integrate**
- **Less expensive**
- **Aerodynamically efficient**
- **Has low observable shaping, hence less IR signature**
- **Has rapid response capability**

Fig. 2

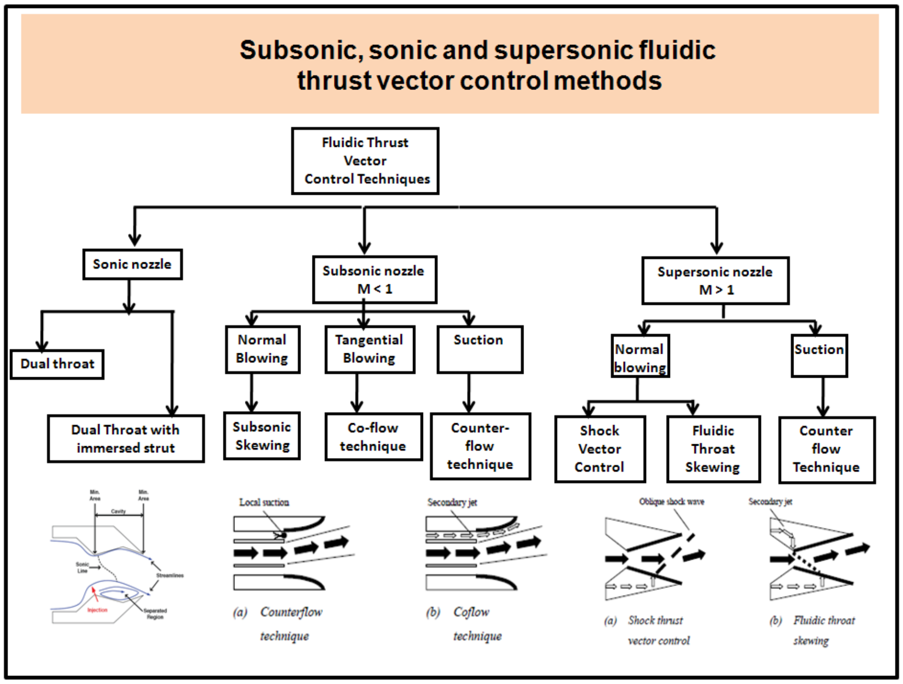


Fig. 3

(Adopted from ref. AIAA-2007-5084, AIAA-3800, http://www.geocities.ws/m_mason007/Paper.pdf)

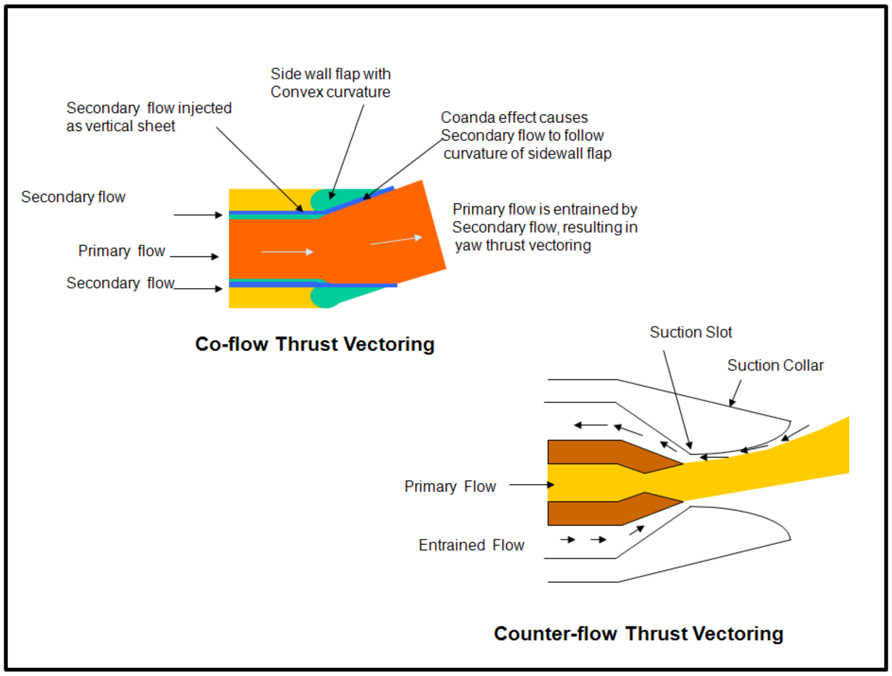


Fig. 4a. (Ref. NASA TM 4574,)

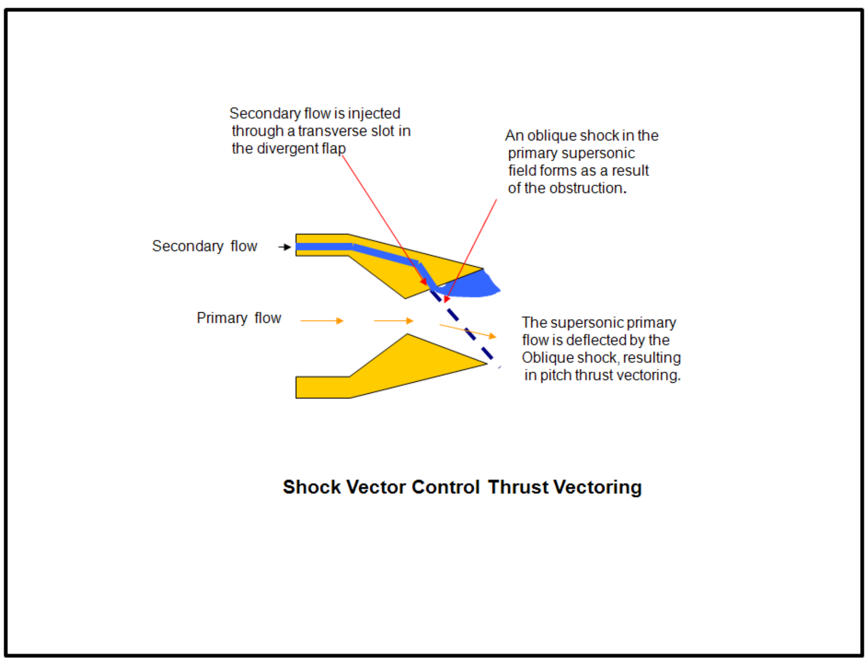


Fig. 4b. (Ref. NASA TM 4574,)

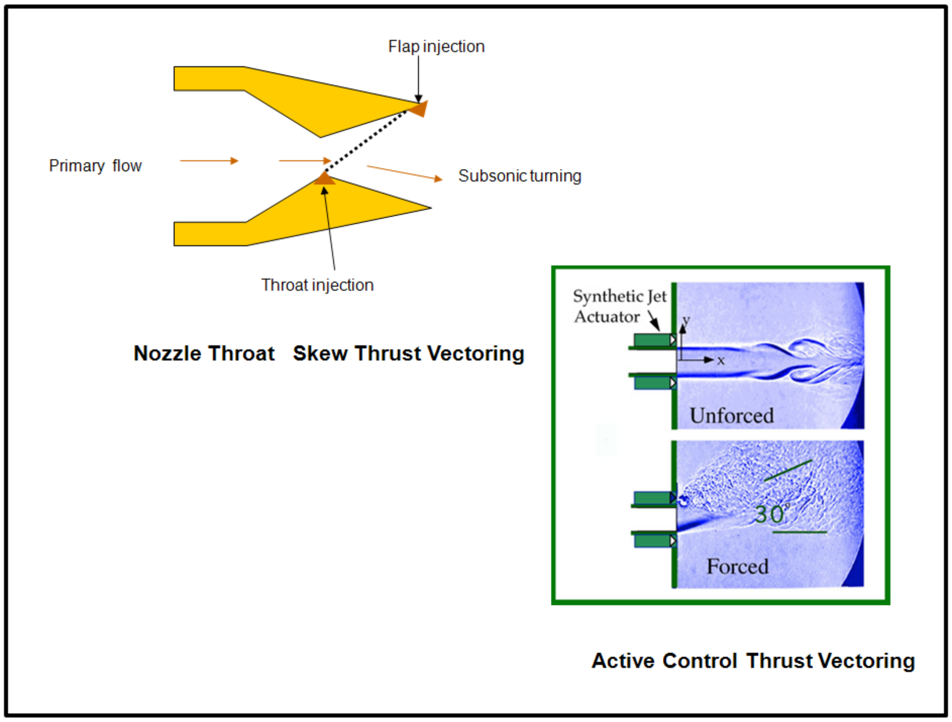


Fig. 4c.

(Ref. NASA TM 4574 & http://aa.dlut.edu.cn/doc/Homepages/GUAN_Hui/Jet-paper/p001-1.pdf)

Fluidic Thrust Vectoring Techniques

Table-1

Method of Fluidic Thrust Vectoring	Features
Counter flow	Viable suction source, as well as thrust loss, weight penalty, potential vectoring instability associated with a highly over expanded nozzle.
Active flow control	Used so-called synthetic jet actuator, injected at the tip of the nozzle . These actuators are used for jet vectoring by exciting the jet shear layer in such a way to either push or pull the primary jet. Unfortunately, the amplitude of the jet actuator was not adequate to produce any jet vectoring at jet Mach number of 0.4 or greater.
Shock – based thrust vector control	Oblique shock generated by introducing an injected flow into a supersonic primary nozzle flow. Approach is characterized by large nozzle flap divergence, large thrust losses, moderate variation in vector angle with changes in nozzle pressure ratio.
Fluidic throat skewing	Symmetric injection around the throat region to provide aerodynamic throttling for Jet area control and assymetric injection to subsonically skew the sonic plane for thrust vector control. Subsonic turning of the nozzle primary flow as opposed to flow turning by formation of a shock.
Dual throat nozzle and variant	Valid only for sonic nozzles. Restriction of nozzle height – can be overcome by an smart immersed strut ; enabling primary flow diversion and reinjection

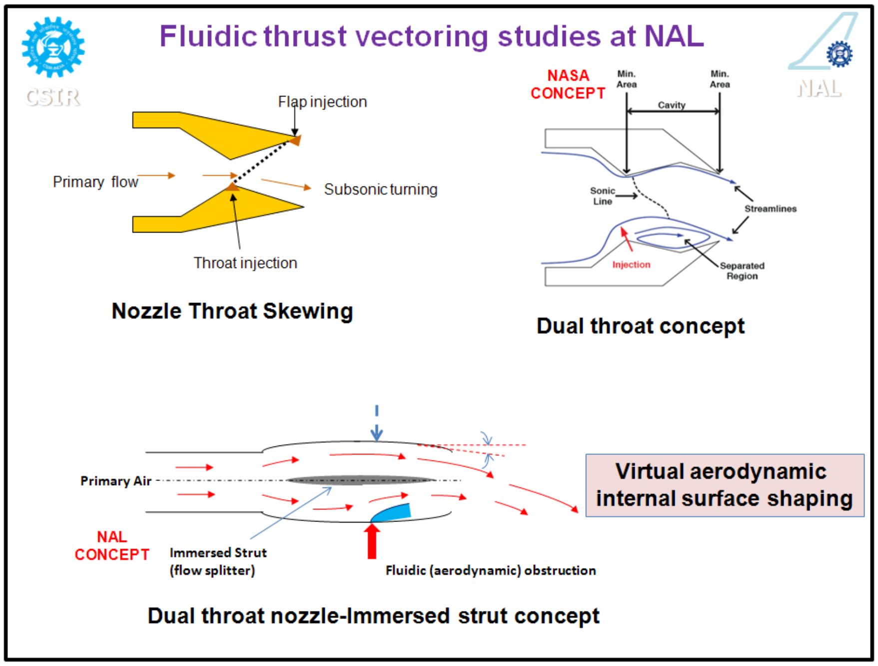

Fluidic thrust vectoring studies at NAL
CSIR
NAL
Flap injection
Primary flow
Subsonic turning
Throat injection
Nozzle Throat Skewing
NASA CONCEPT
Min. Area
Min. Area
Cavity
Sonic Line
Streamlines
Injection
Separated Region
Dual throat concept
Primary Air
NAL CONCEPT
Immersed Strut (flow splitter)
Fluidic (aerodynamic) obstruction
Virtual aerodynamic internal surface shaping
Dual throat nozzle-Immersed strut concept

Fig. 5

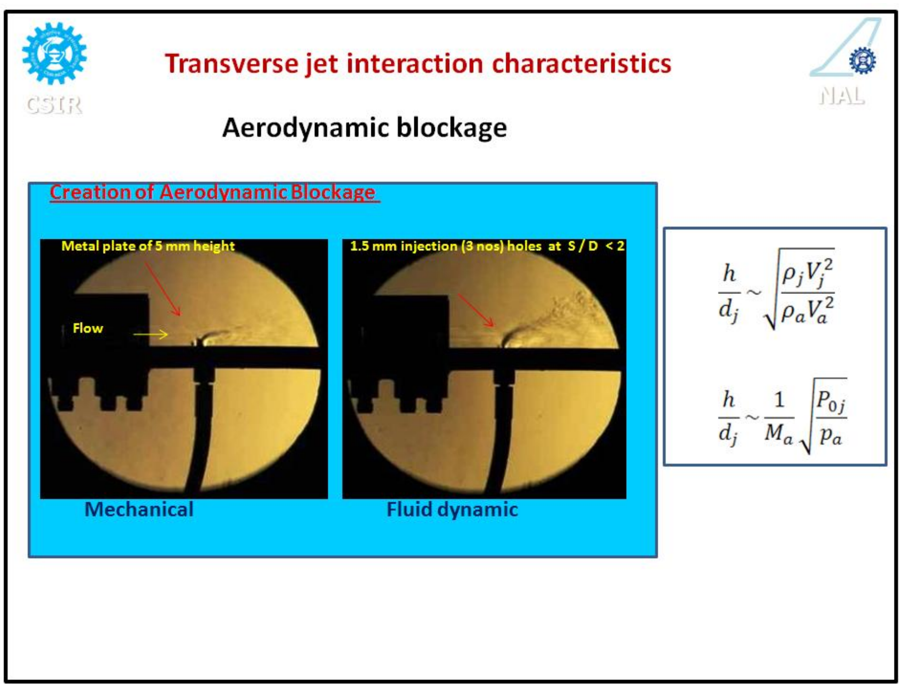

Transverse jet interaction characteristics
CSIR
NAL
Aerodynamic blockage
Creation of Aerodynamic Blockage
Metal plate of 5 mm height
Flow
1.5 mm injection (3 nos) holes at S / D < 2
Mechanical
Fluid dynamic
$\frac{h}{d_j} \sim \sqrt{\frac{\rho_j V_j^2}{\rho_a V_a^2}}$
$\frac{h}{d_j} \sim \frac{1}{M_a}\sqrt{\frac{P_{0j}}{p_a}}$

Fig. 6

Jet Interaction Parameter

$$\frac{h}{d_j} \sim \sqrt{\frac{P_{0j}}{P_a}}$$ for a given primary flow Mach number

Aerodynamic blockage for 2D flow $B_a \sim h \sim d_j\sqrt{P_{0j}}$

$$\dot{m}_j = \rho_j A_j V_j = \frac{p_j}{RT_j}\frac{\pi}{4}d_j^2\sqrt{\gamma R T_j}$$

$$T_{0j} = T_j\left(1+\frac{\gamma-1}{2}M^2\right)$$

$$\frac{P_{0j}}{p_j} = \left(1+\frac{\gamma-1}{2}M^2\right)^{\frac{\gamma}{\gamma-1}}$$

$$\left.\begin{aligned} T_{0j} &\sim T_j \\ P_{0j} &\sim p_j \end{aligned}\right\}$$ For a choked secondary jet

$$\dot{m}_j \sim P_{0j}d_j^2$$

Jet Interaction Parameter $$\varphi \sim \frac{B_a}{\dot{m}_j} \sim \frac{d_j\sqrt{P_{0j}}}{P_{0j}d_j^2} \sim \frac{1}{d_j\sqrt{P_{0j}}} \sim \frac{1}{\sqrt{P_{0j}A_j}}$$

Fig. 7

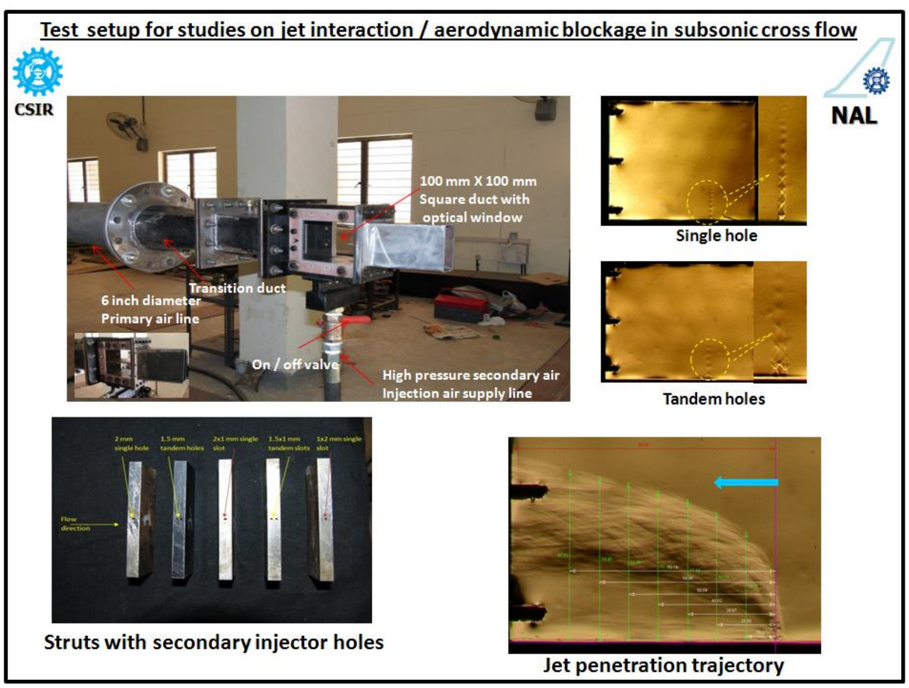


Fig. 8

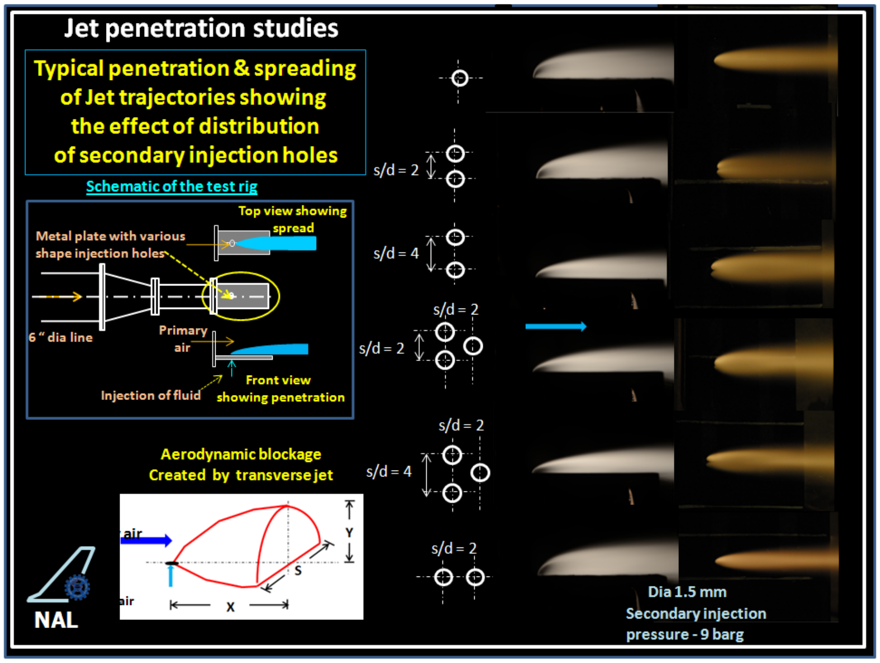


Fig. 9 Jet penetration and spreading

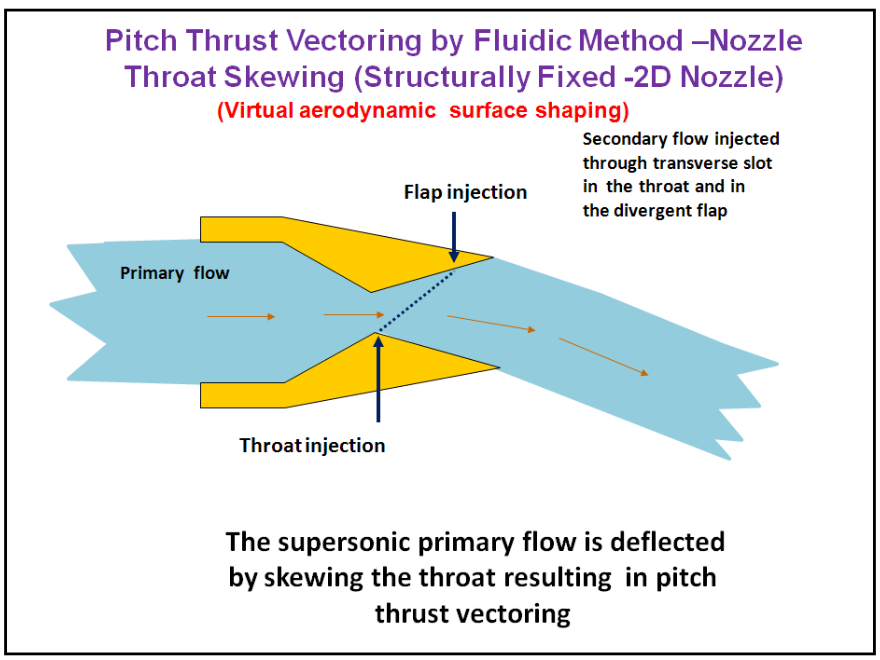


Fig. 10

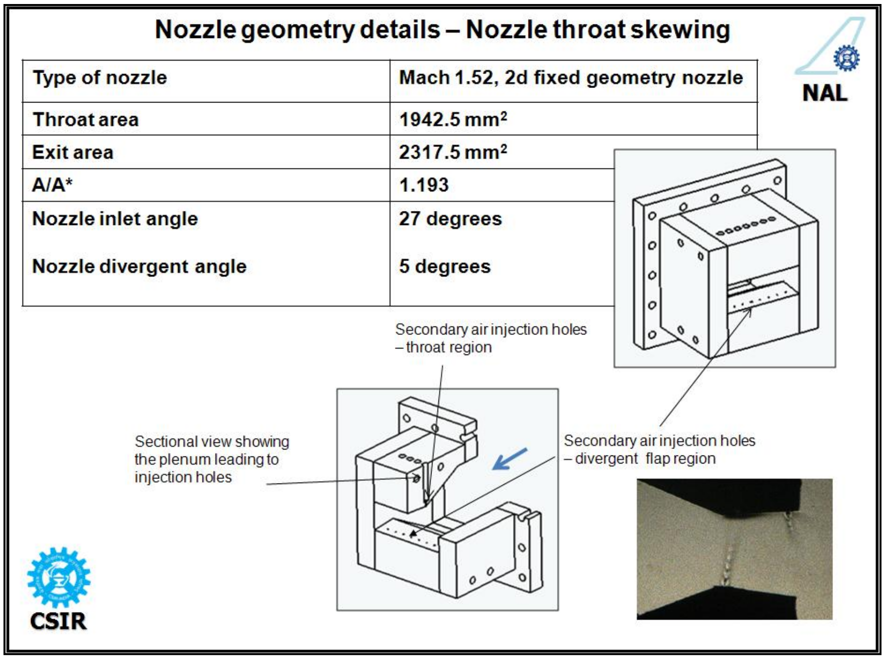
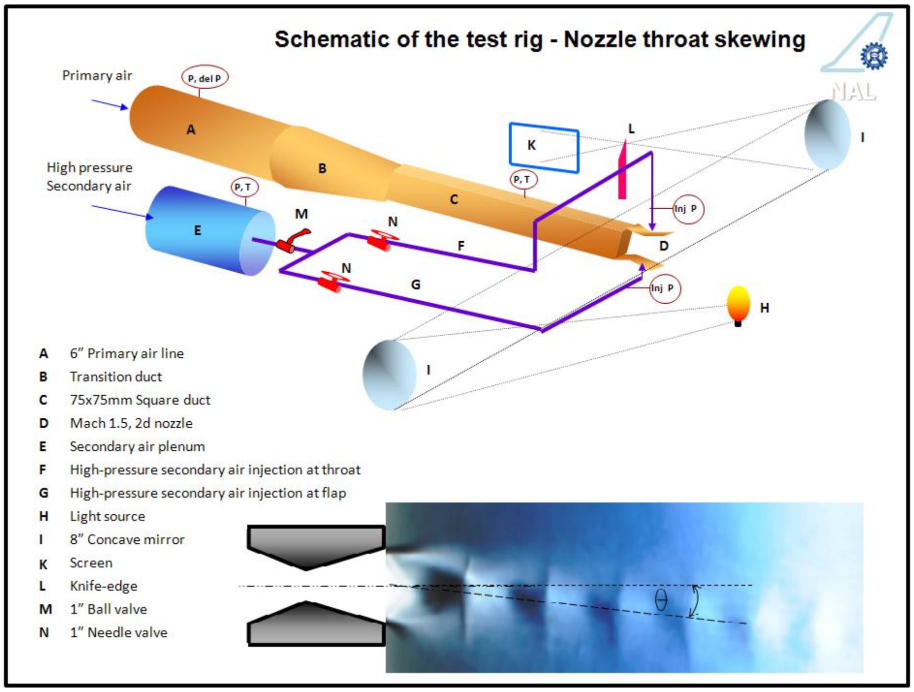

Nozzle geometry details – Nozzle throat skewing
Type of nozzle
Mach 1.52, 2d fixed geometry nozzle
Throat area
1942.5 mm²
Exit area
2317.5 mm²
A/A*
1.193
Nozzle inlet angle
27 degrees
Nozzle divergent angle
5 degrees
NAL
Secondary air injection holes – throat region
Sectional view showing the plenum leading to injection holes
Secondary air injection holes – divergent flap region
CSIR

Fig. 11

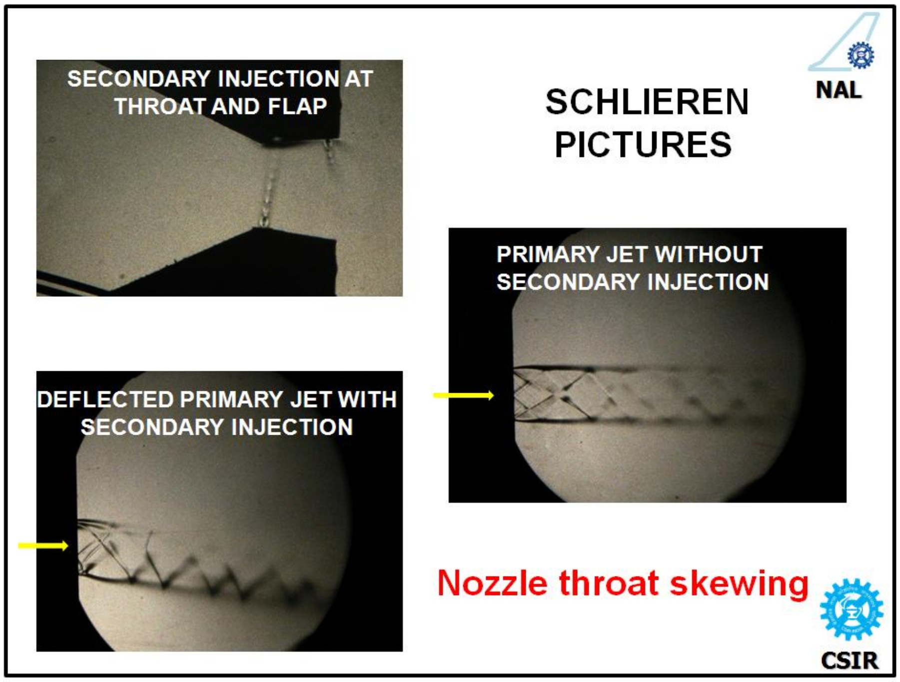

NOZZLE SHOWING INJECTION HOLES
CLOSE-UP VIEW OF NOZZLE
Throat injection
NOZZLE WITH SIDE PLATE REMOVED
Flap injection
NAL

Fig. 12



Schematic of the test rig - Nozzle throat skewing
NAL
Primary air
P, del P
High pressure
Secondary air
P, T
A
B
C
D
E
F
G
H
I
K
L
M
N
Inj P
A 6" Primary air line
B Transition duct
C 75x75mm Square duct
D Mach 1.5, 2d nozzle
E Secondary air plenum
F High-pressure secondary air injection at throat
G High-pressure secondary air injection at flap
H Light source
I 8" Concave mirror
K Screen
L Knife-edge
M 1" Ball valve
N 1" Needle valve
θ

Fig. 13



SECONDARY INJECTION AT THROAT AND FLAP
SCHLIEREN PICTURES
NAL
PRIMARY JET WITHOUT SECONDARY INJECTION
DEFLECTED PRIMARY JET WITH SECONDARY INJECTION
Nozzle throat skewing
CSIR

Fig. 14

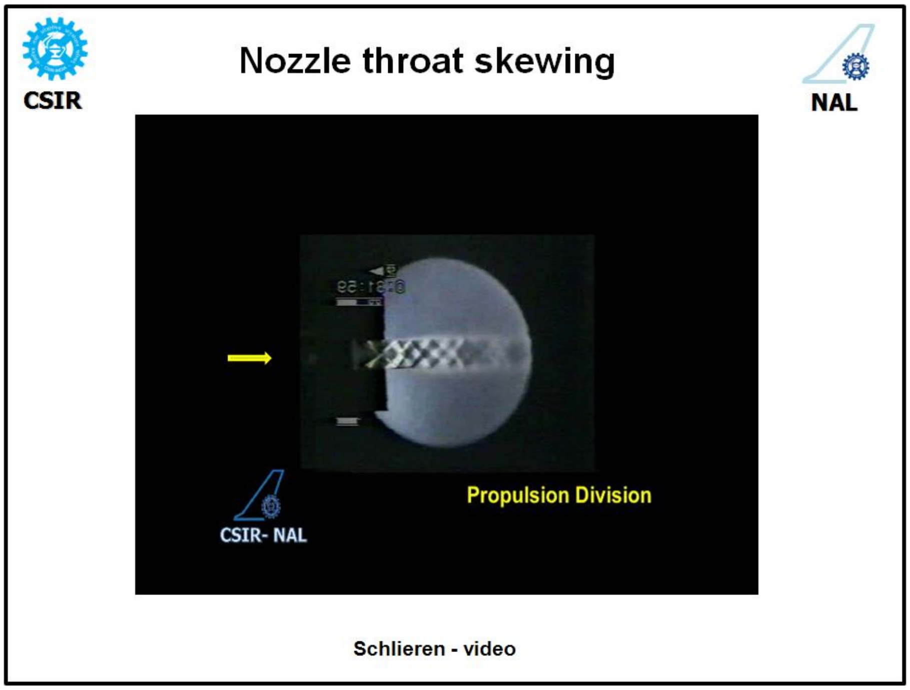

CSIR
Nozzle throat skewing
NAL
Propulsion Division
CSIR- NAL
Schlieren - video

Fig. 15

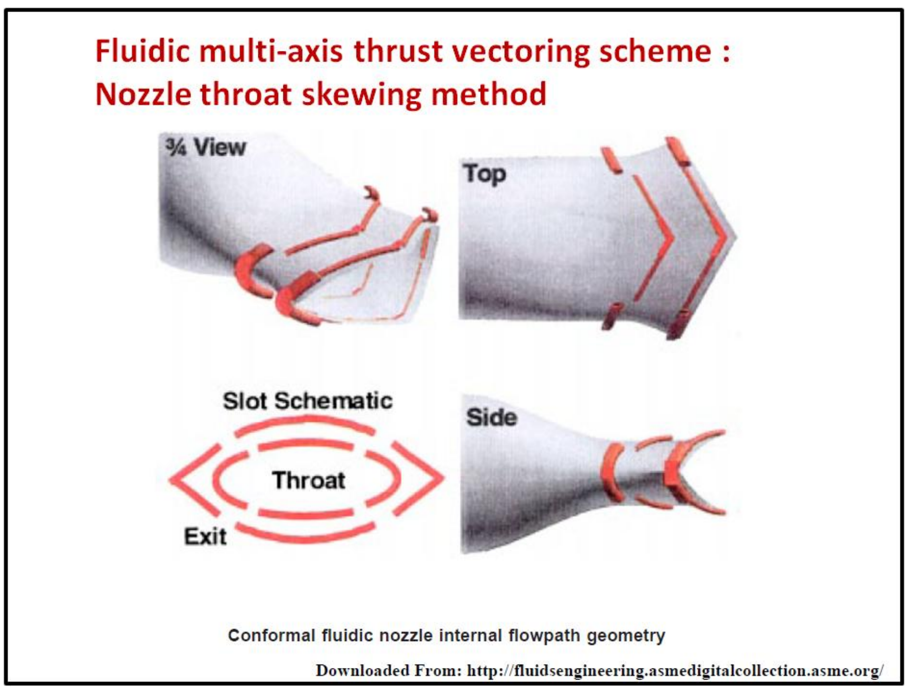
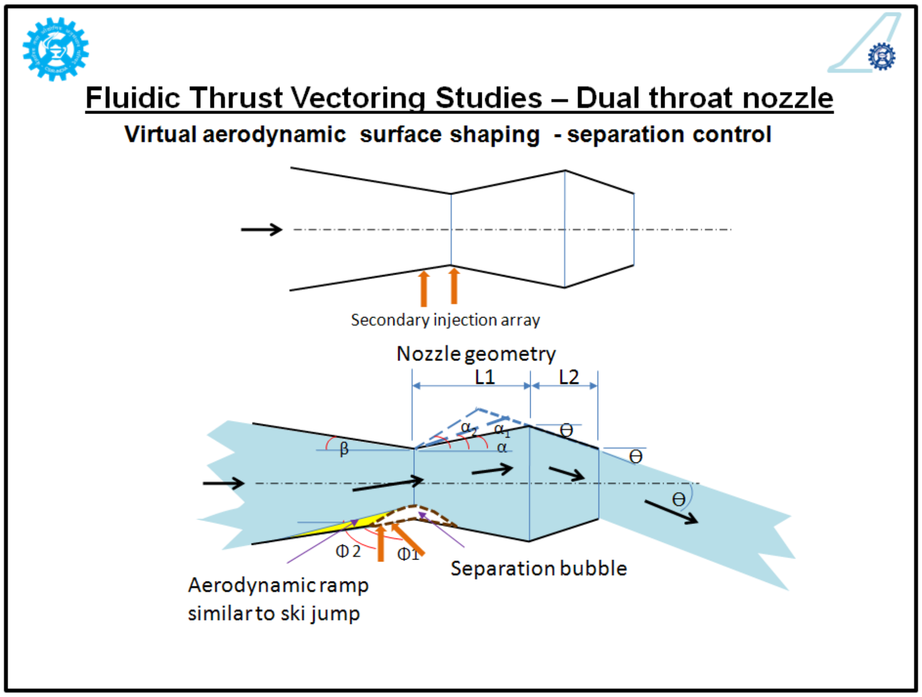
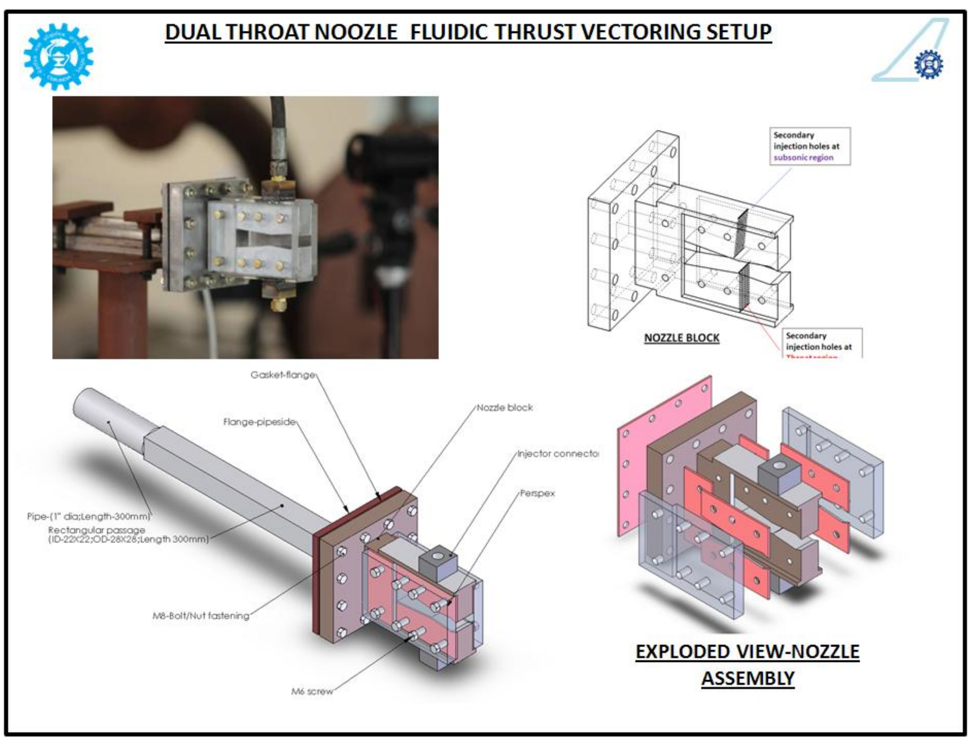

Fluidic multi-axis thrust vectoring scheme :
Nozzle throat skewing method
¾ View
Top
Slot Schematic
Throat
Exit
Side
Conformal fluidic nozzle internal flowpath geometry
Downloaded From: http://fluidsengineering.asmedigitalcollection.asme.org/

Fig. 16



Fluidic Thrust Vectoring Studies – Dual throat nozzle
Virtual aerodynamic surface shaping - separation control
Secondary injection array
Nozzle geometry
L1
L2
β
α
θ
Φ 2
Φ1
Separation bubble
Aerodynamic ramp
similar to ski jump

Fig. 17



DUAL THROAT NOOZLE FLUIDIC THRUST VECTORING SETUP
Secondary injection holes at subsonic region
NOZZLE BLOCK
Secondary injection holes at
Gasket-flange
Flange-pipeside
Nozzle block
Injector connecto
Perspex
Pipe-(1" dia;Length-300mm)
Rectangular passage (ID-22X22;OD-28X28;Length 300mm)
M8-Bolt/Nut fastening
M6 screw
EXPLODED VIEW-NOZZLE
ASSEMBLY

Fig. 18

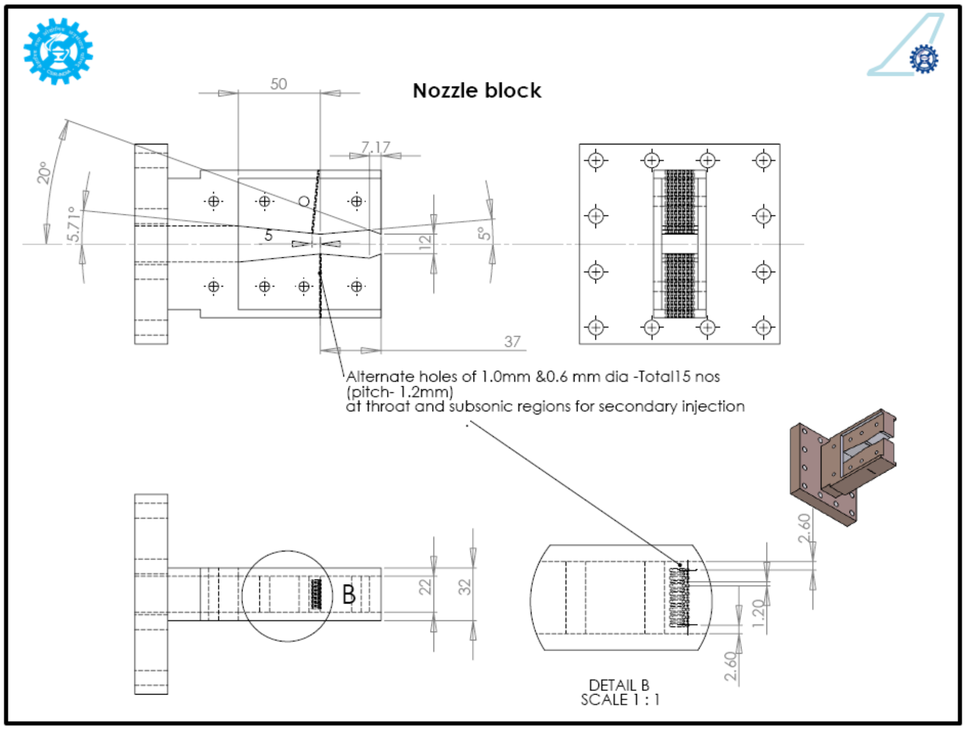

Nozzle block
50
7.17
20°
5.71°
5
12
5°
37
Alternate holes of 1.0mm &0.6 mm dia -Total15 nos
(pitch- 1.2mm)
at throat and subsonic regions for secondary injection
B
22
32
2.60
1.20
2.60
DETAIL B
SCALE 1 : 1

Fig. 19

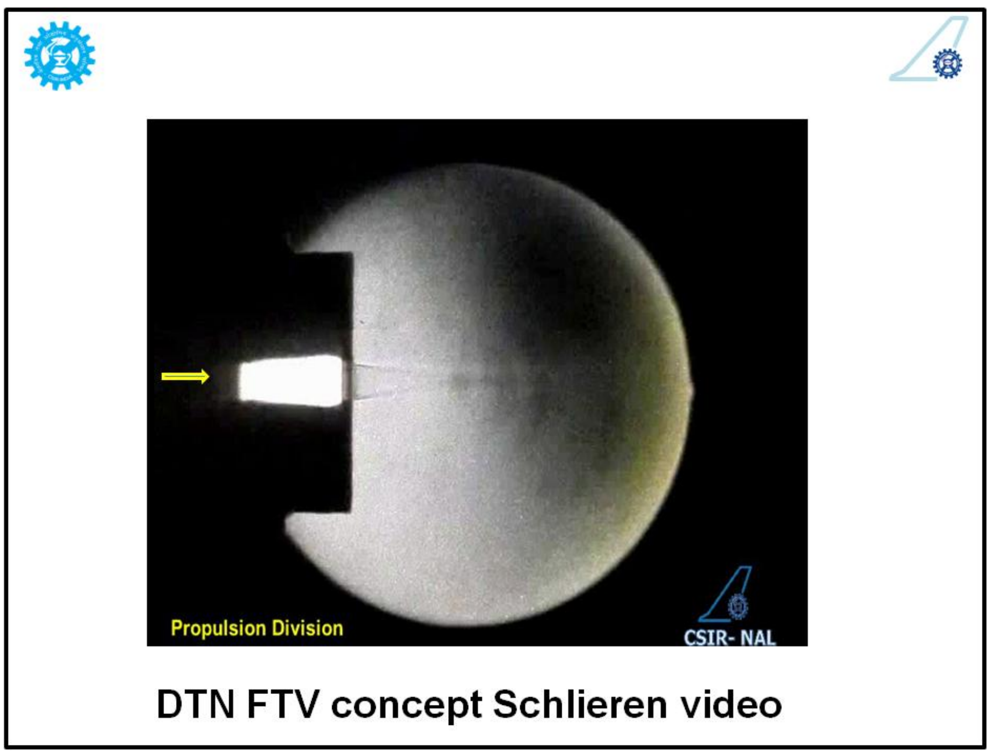
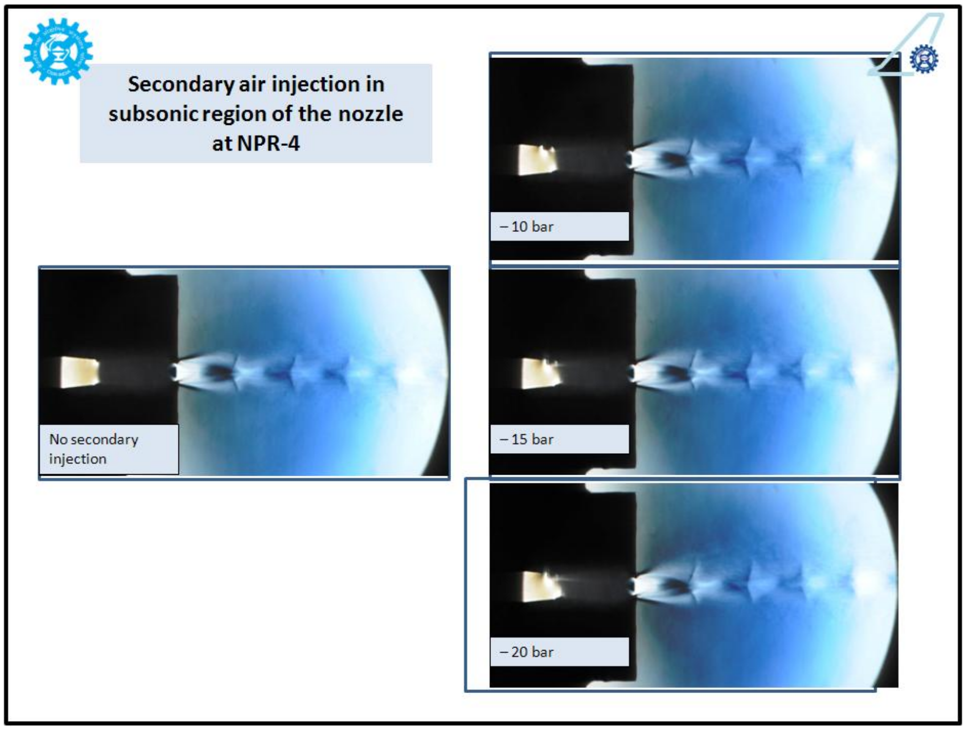
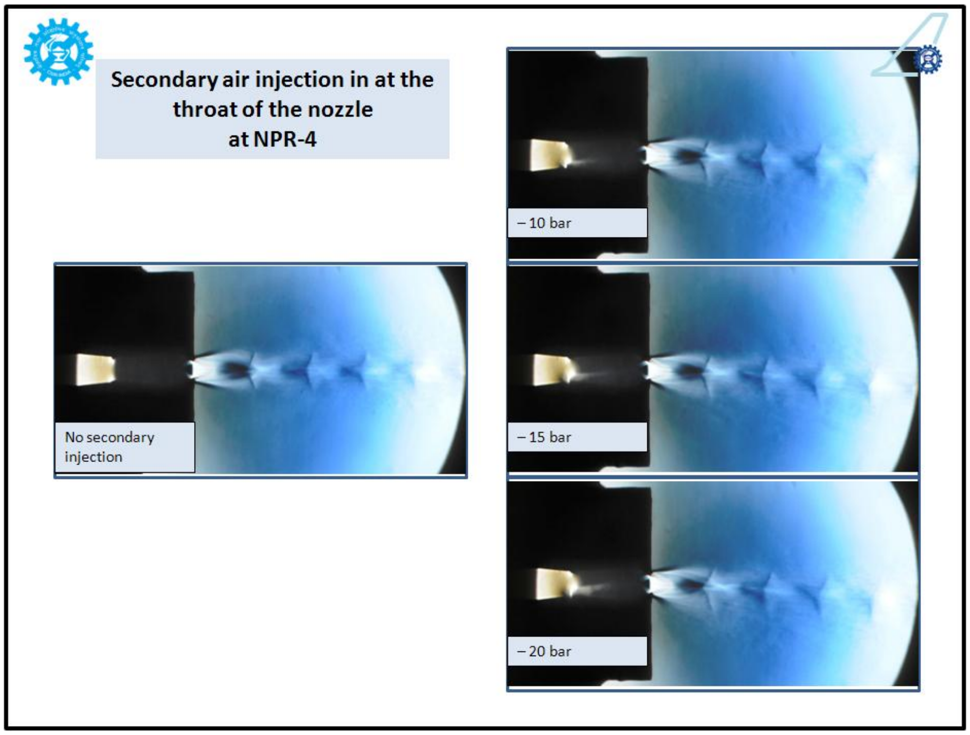

Propulsion Division
CSIR- NAL
DTN FTV concept Schlieren video

Fig. 20



Secondary air injection in subsonic region of the nozzle at NPR-4
No secondary injection
– 10 bar
– 15 bar
– 20 bar

Fig. 21



Secondary air injection in at the throat of the nozzle at NPR-4
No secondary injection
– 10 bar
– 15 bar
– 20 bar

Fig. 22

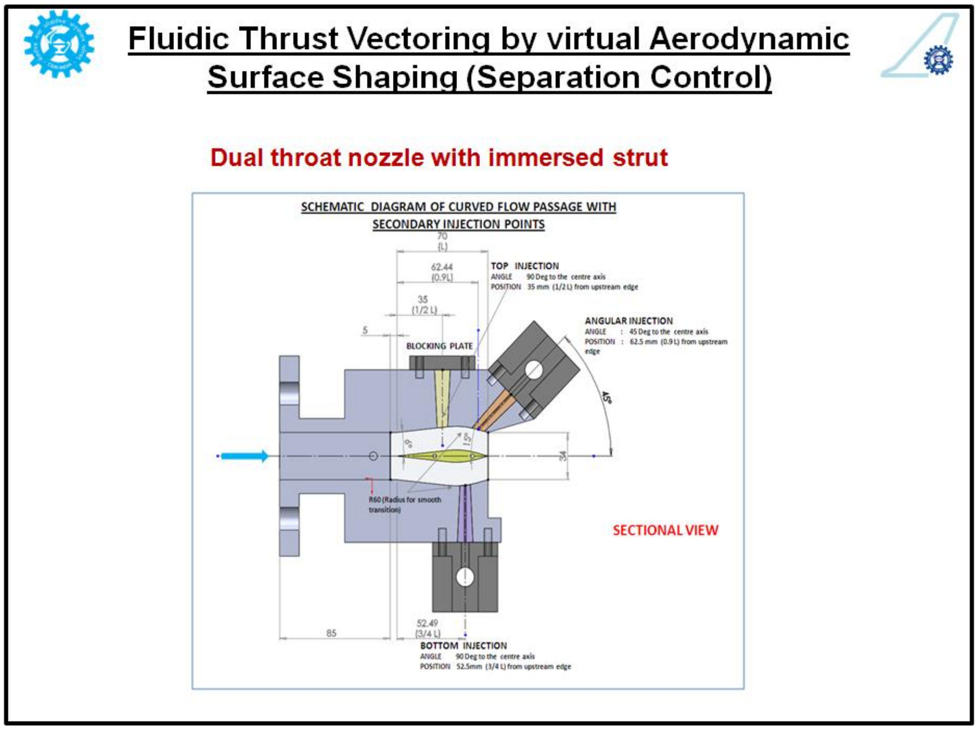


Fig. 23

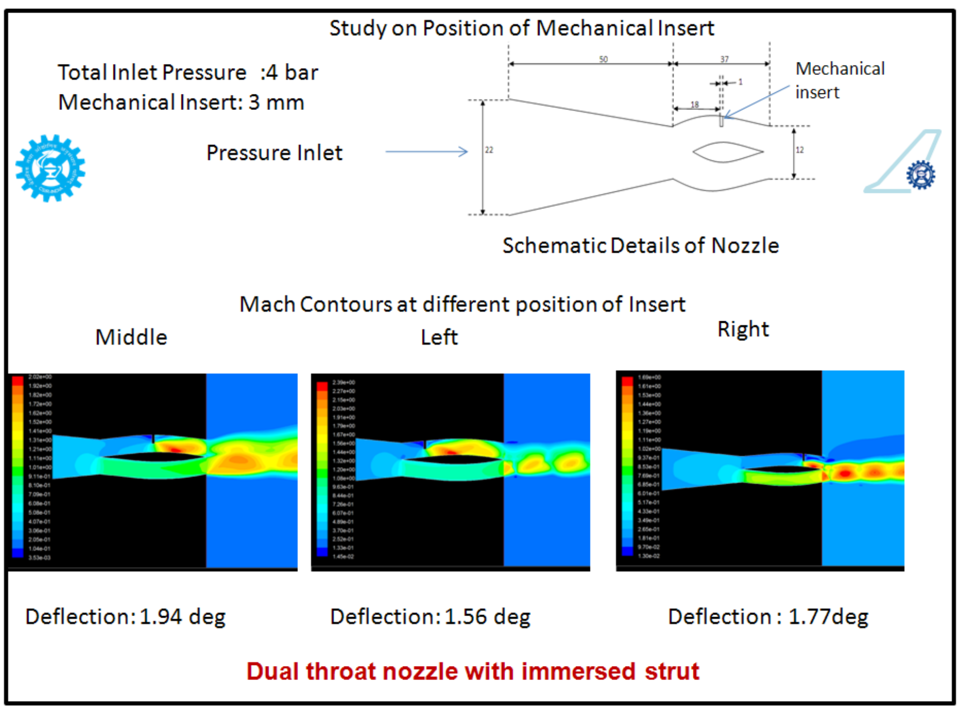
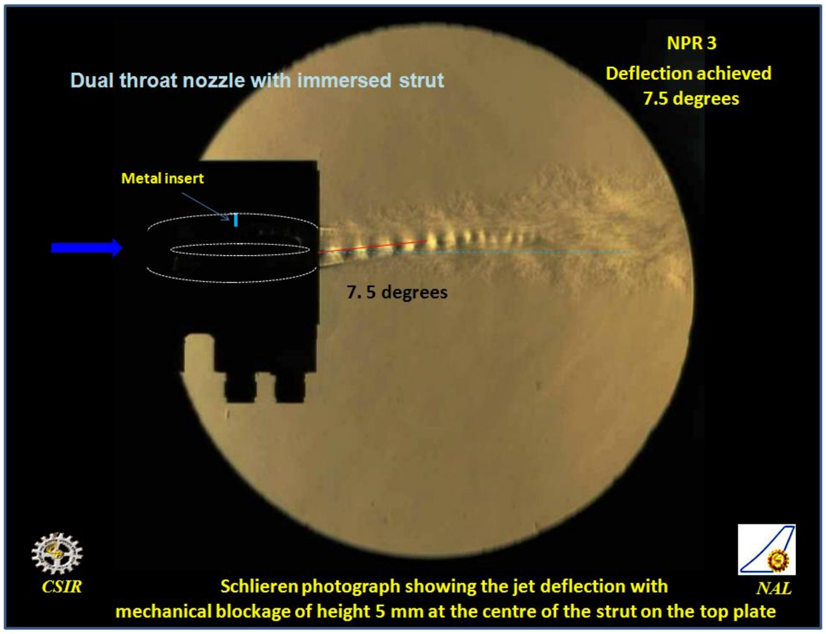
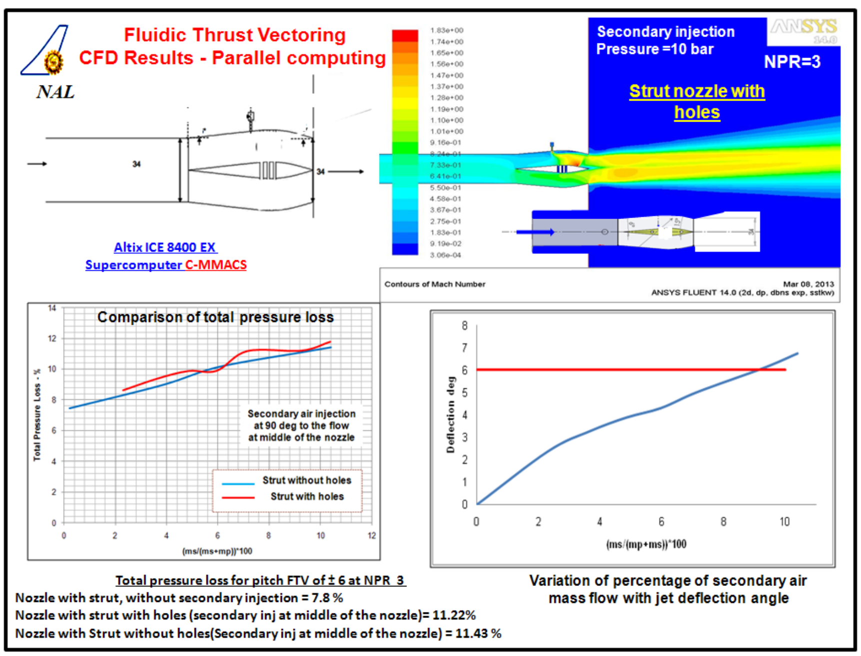


Fig. 24 – Equivalence of mechanical and aerodynamic blockage



Dual throat nozzle with immersed strut
NPR 3
Deflection achieved
7.5 degrees
Metal insert
7. 5 degrees
CSIR
NAL
Schlieren photograph showing the jet deflection with
mechanical blockage of height 5 mm at the centre of the strut on the top plate

Fig. 25



Fluidic Thrust Vectoring
CFD Results - Parallel computing
NAL
Altix ICE 8400 EX
Supercomputer C-MMACS
Secondary injection
Pressure =10 bar
NPR=3
Strut nozzle with
holes
Contours of Mach Number
Mar 08, 2013
ANSYS FLUENT 14.0 (2d, dp, dbns exp, sstkw)
Comparison of total pressure loss
Total Pressure Loss - %
Secondary air injection
at 90 deg to the flow
at middle of the nozzle
Strut without holes
Strut with holes
(ms/(ms+mp))*100
Deflection deg
(ms/(mp+ms))*100
Total pressure loss for pitch FTV of ± 6 at NPR 3
Nozzle with strut, without secondary injection = 7.8 %
Nozzle with strut with holes (secondary inj at middle of the nozzle)= 11.22%
Nozzle with Strut without holes(Secondary inj at middle of the nozzle) = 11.43 %
Variation of percentage of secondary air
mass flow with jet deflection angle

Fig. 26

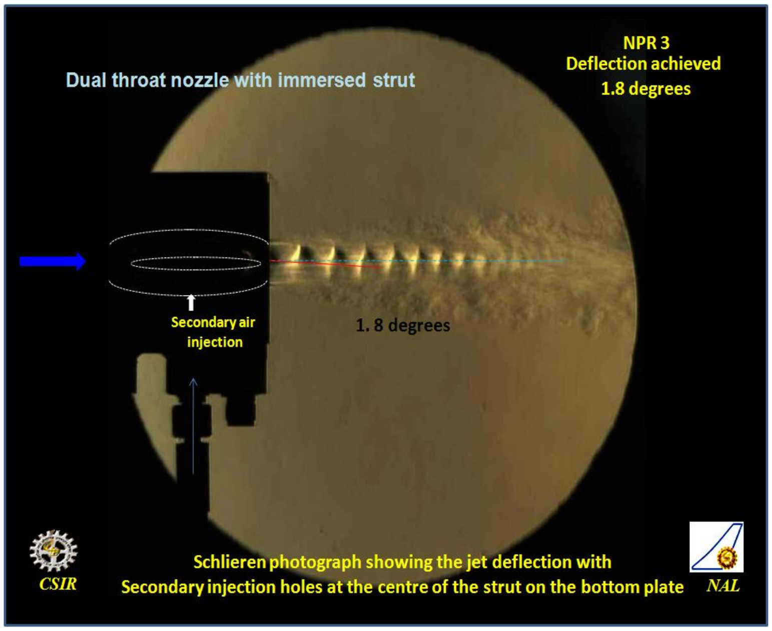

NPR 3
Deflection achieved
1.8 degrees
Dual throat nozzle with immersed strut
Secondary air injection
1. 8 degrees
CSIR
Schlieren photograph showing the jet deflection with
Secondary injection holes at the centre of the strut on the bottom plate
NAL

Fig. 27

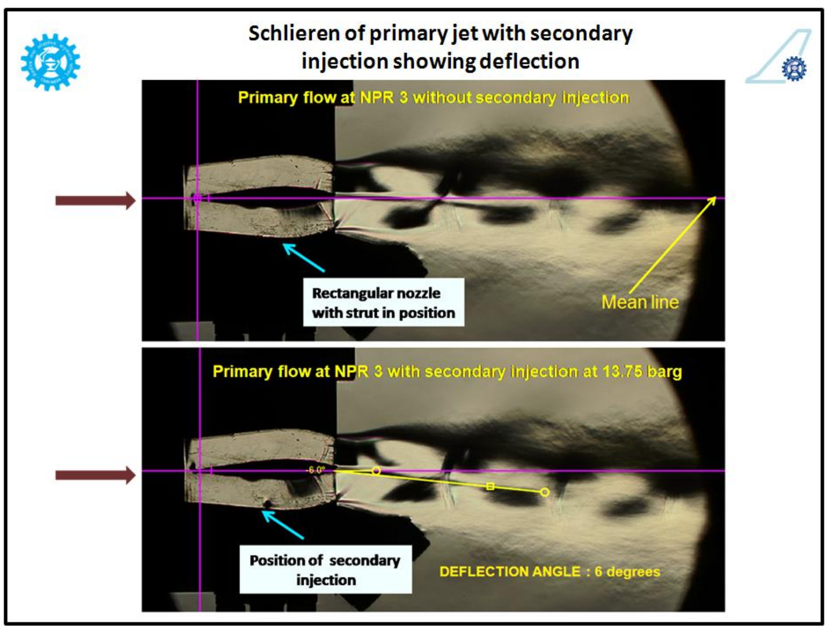

Schlieren of primary jet with secondary injection showing deflection
Primary flow at NPR 3 without secondary injection
Rectangular nozzle with strut in position
Mean line
Primary flow at NPR 3 with secondary injection at 13.75 barg
6.0°
Position of secondary injection
DEFLECTION ANGLE : 6 degrees

Fig. 28

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Abstract:

The Propulsion Division, NAL has built-up a comprehensive, experimentally validated, design data base for the Fluidic Thrust Vectoring of sonic and supersonic aero-engine exhausts, using the concepts of shock vector control and virtual aerodynamic surface shaping (nozzle throat skewing and separation control (dual throat and its variant with an immersed strut)). This report gives the salient features of the recent work carried out.